

## **Development of a Novel Coupled Simulation Tool to Study Ocean-Estuary Exchange**

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### **LONG-TERM GOALS**

The long-term goal of this project is to develop a coupled ocean-estuary simulation tool that will consist of the Regional Oceanic Modeling System (ROMS) and the nonhydrostatic, unstructured-grid SUNTANS model, in order to study the interaction of coastal regions with estuaries. The scientific goal will be to understand the dynamics of ocean-estuary exchange between San Francisco Bay and the coastal Pacific Ocean, with ROMS simulating the coastal Pacific Ocean, and SUNTANS simulating San Francisco Bay.

### **OBJECTIVES**

The primary objective of this project is to develop and implement a coupled hydrodynamics and sediment-transport simulation tool to study the complex three-dimensional, coupled ocean-estuary processes that influence exchange through the Golden Gate channel in San Francisco Bay. In order to understand the influence of regional processes in the coastal ocean and how they are coupled to local processes in San Francisco Bay, the project will employ a one-way coupled simulation tool, in which a model for San Francisco Bay is coupled to a regional model for the coastal Pacific Ocean. The SUNTANS model (Fringer et al., 2006) will be employed to simulate flow in San Francisco Bay, and it will obtain boundary conditions at the coastal ocean from simulations of the California coastal current using ROMS (Shchepetkin and McWilliams, 2005). SUNTANS is well-suited to simulate the exchange flow at the Golden Gate because it employs an unstructured grid, which enables simulation domains that include the entire Bay while also resolving finescale flow features near the Golden Gate. Furthermore, because SUNTANS is a nonhydrostatic code, it will capture nonhydrostatic features of the exchange flow which may be important at high resolution. ROMS, on the other hand, was originally written to simulate regional flows like the California Coastal Current, and employs highly accurate methods to simulate the complex dynamics of upwelling fronts, jets, and squirts over seasonal time scales. Using a stand-alone SUNTANS, simulations will be performed in idealized domains to understand the fundamental mechanisms governing three-dimensional exchange. In the real, field-scale domain, one-way coupling will be used to understand how tidal and seasonal variability in the

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coastal currents as well as in the Bay influence the dynamics of ocean-estuary exchange through the Golden Gate channel.

## **APPROACH**

Simulations of San Francisco Bay employ SUNTANS (Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator), a free-surface, nonhydrostatic, unstructured-grid, parallel coastal ocean and estuary simulation tool that solves the Navier-Stokes equations under the Boussinesq approximation (Fringer et al., 2006a). The influence of coastal currents on exchange between San Francisco Bay and the coastal Pacific is incorporated with one-way coupling of the SUNTANS model with the ROMS model (Shchepetkin and McWilliams, 2005). In one-way coupling, the SUNTANS model is driven by low-frequency currents from the ROMS model while the ROMS model does not feel the effects of the SUNTANS model.

## **WORK COMPLETED**

We have assessed numerical diffusion in the SUNTANS model by studying tracer dispersion in San Francisco Bay and by developing expressions for the numerical diffusion arising from the modified equivalent partial differential equation analysis of the governing numerical discretization of the transport equation. We have also simulated and analyzed observed currents and free-surface heights in San Francisco Bay to understand the impact of the Pacific Ocean on low-frequency variability of the Bay.

## **RESULTS**

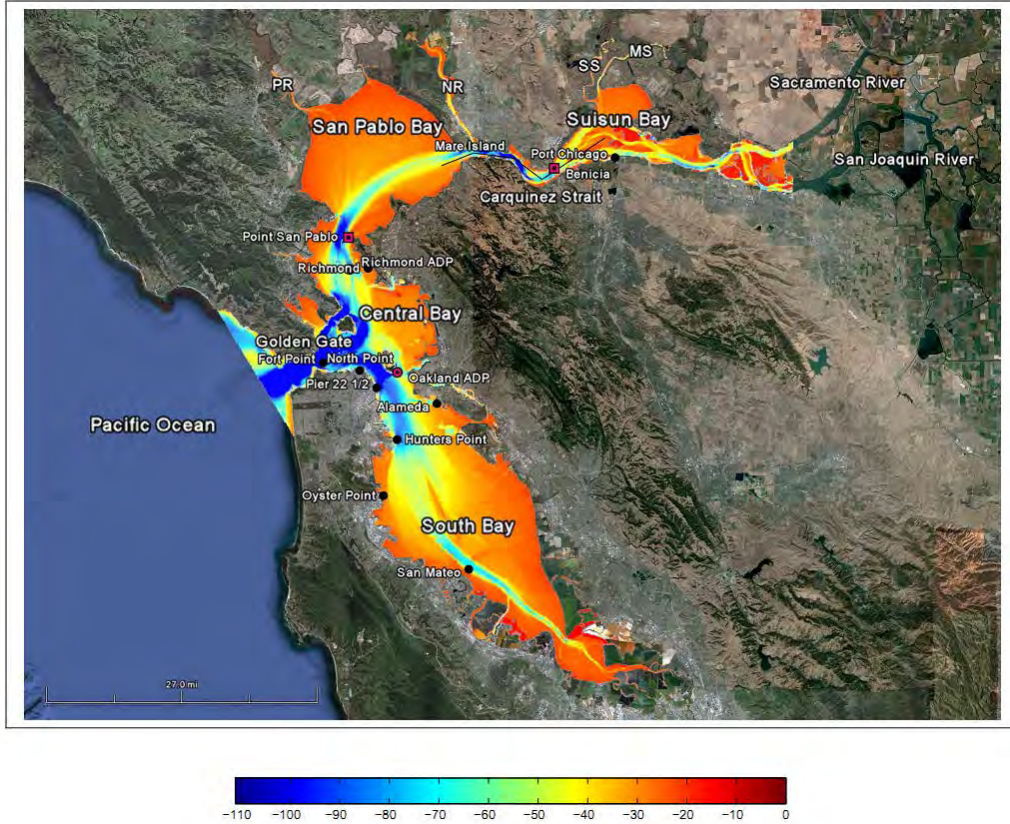
### *Numerical diffusion in San Francisco Bay*

We performed simulations of tracer transport in San Francisco Bay using the setup described in Chua and Fringer (2011) to assess the impact of tidal strain on numerical diffusion. A passive tracer field was initialized at three locations in San Francisco Bay (see Figure 1), each of which has different hydrodynamics that affect tidal strain. At the Golden Gate, strong tidal currents in deep water lead to strong straining with relatively weak stratification. In Carquinez Strait, strong tidal currents are accompanied by strong vertical shear due to gravitational circulation. The third initial tracer is located on the shallow shoals in South San Francisco Bay where there is little tidal strain. Figures 2 and 3 depict the evolution of the tracer field in Carquinez Strait while Figures 4 and 5 depict the evolution in South San Francisco Bay. The results of first-order upwind are compared to those of a second-order TVD scheme that ensures monotonicity following the formulation of Casulli and Zanolli (2005). Due to the high strain in Carquinez Strait, strong gradients arise that lead to grid-scale variability that induces extensive numerical diffusion in both schemes. Therefore, the results of the first- and second-order schemes are qualitatively similar particularly over a longer time period.

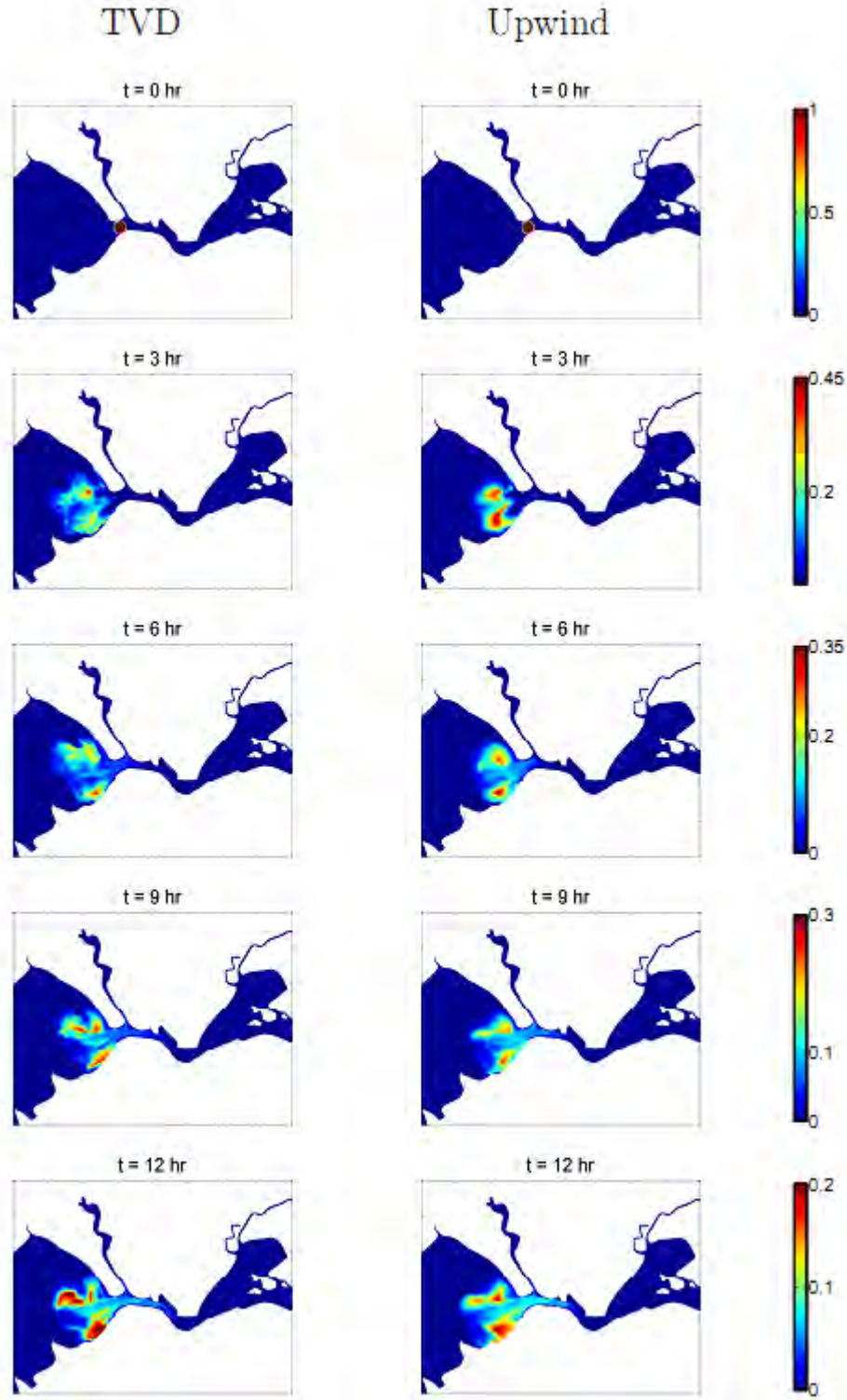
The equation governing the variance of a tracer field  $s$  can be manipulated to give a measure of the net domain-averaged numerical diffusion with

$$k_{net} = \frac{\sum [(s^n)^2 - (s^{n+1})^2] \Delta V}{2\Delta t \sum \nabla^d s^n \cdot \nabla^d s^n \Delta V}, \quad (1)$$

where superscripts  $n$  and  $n+1$  imply the time step,  $\nabla^d$  is the discrete gradient operator and the summation is implied over all discrete volumes in the domain of size  $\Delta V$ . Figure 6 shows time series of the domain-averaged numerical diffusion coefficient at three locations in San Francisco Bay. Although the TVD scheme should produce less numerical diffusion, it produces less numerical diffusion than the first-order upwind scheme only where there is weak tidal strain, such as in South Bay. In locations of large tidal strain (Golden Gate and Carquinez Strait), the numerical diffusion arising from the TVD scheme is less than that from the first-order upwind scheme only during the first day. Otherwise, there is virtually no difference between the numerical diffusion produced by the TVD and first-order schemes. This occurs because the tidal strain leads to grid-scale variability that is smoothed out by diffusion for both the first-order and TVD schemes. Over long time scales this produces results that are identical for the two schemes. Figure 7 shows that the differences between the two schemes are pronounced when the scalar field is reinitialized every hour. Over such short time scales, tidal straining cannot produce grid-scale variability and so the TVD scheme produces markedly less numerical diffusion than the first-order upwind scheme at all three locations in the Bay.

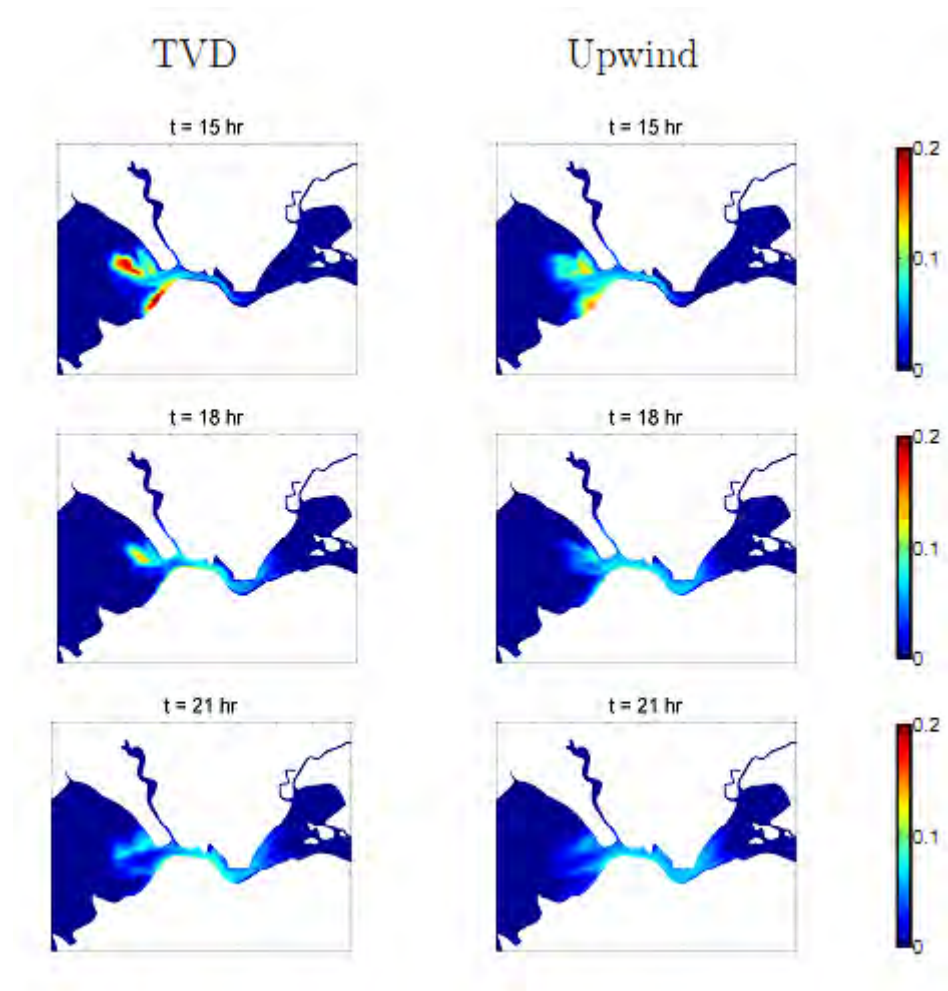


**Figure 1: The San Francisco Bay model domain, bathymetry (in m) and locations of calibration. Legend: Surface elevations (black circles), currents (red circles), salinity (red squares), and vertical profile transect (black line), Petaluma River (PR), Napa River (NR), Suisun Slough (SS), Montezuma Slough (MS).**

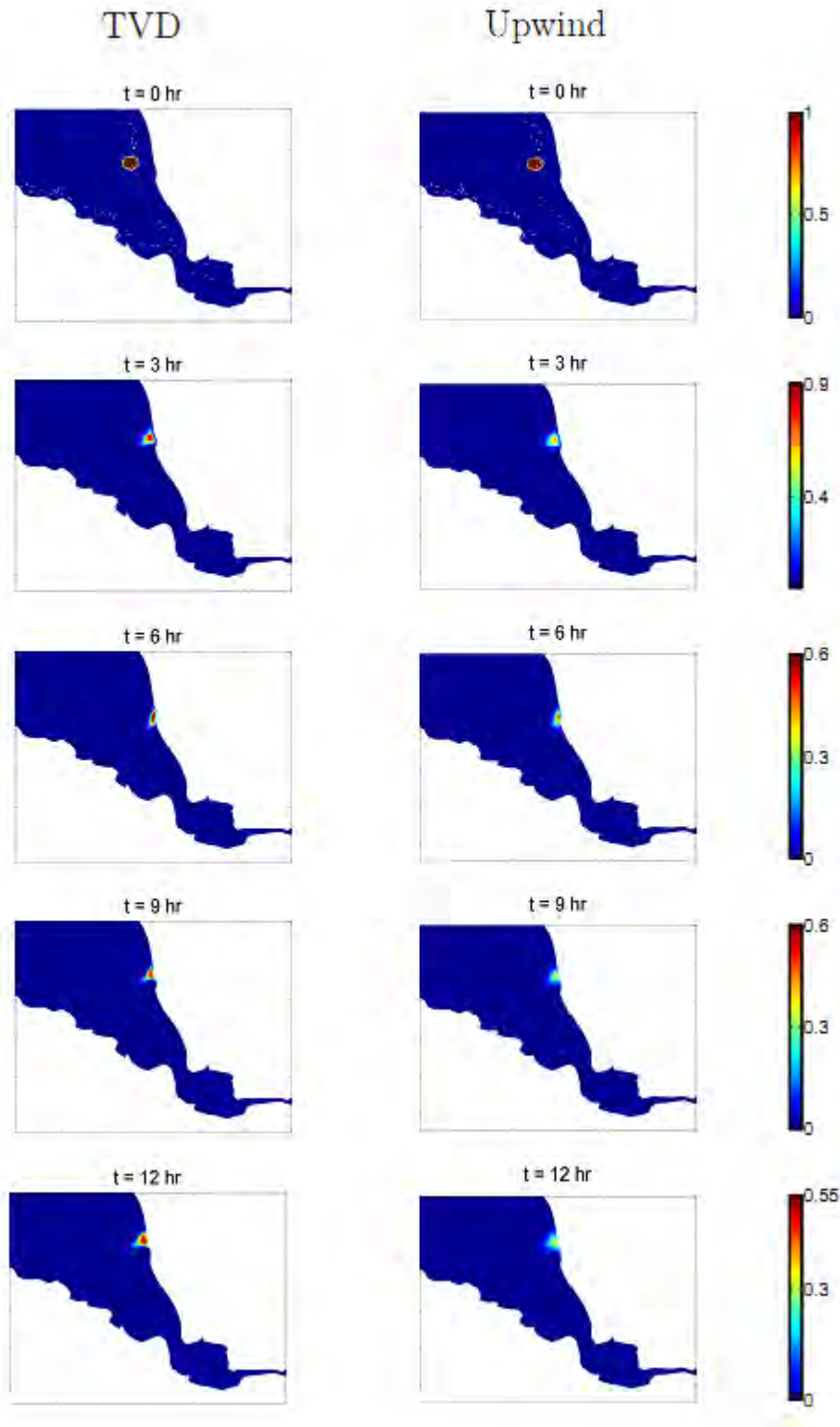


*Figure 2: Evolution of passive tracer field at Carquinez Strait from 0 to 12 hour in 3 hour intervals. Left column is the TVD scheme and right column is first-order upwind. Note that the color axes change with time.*

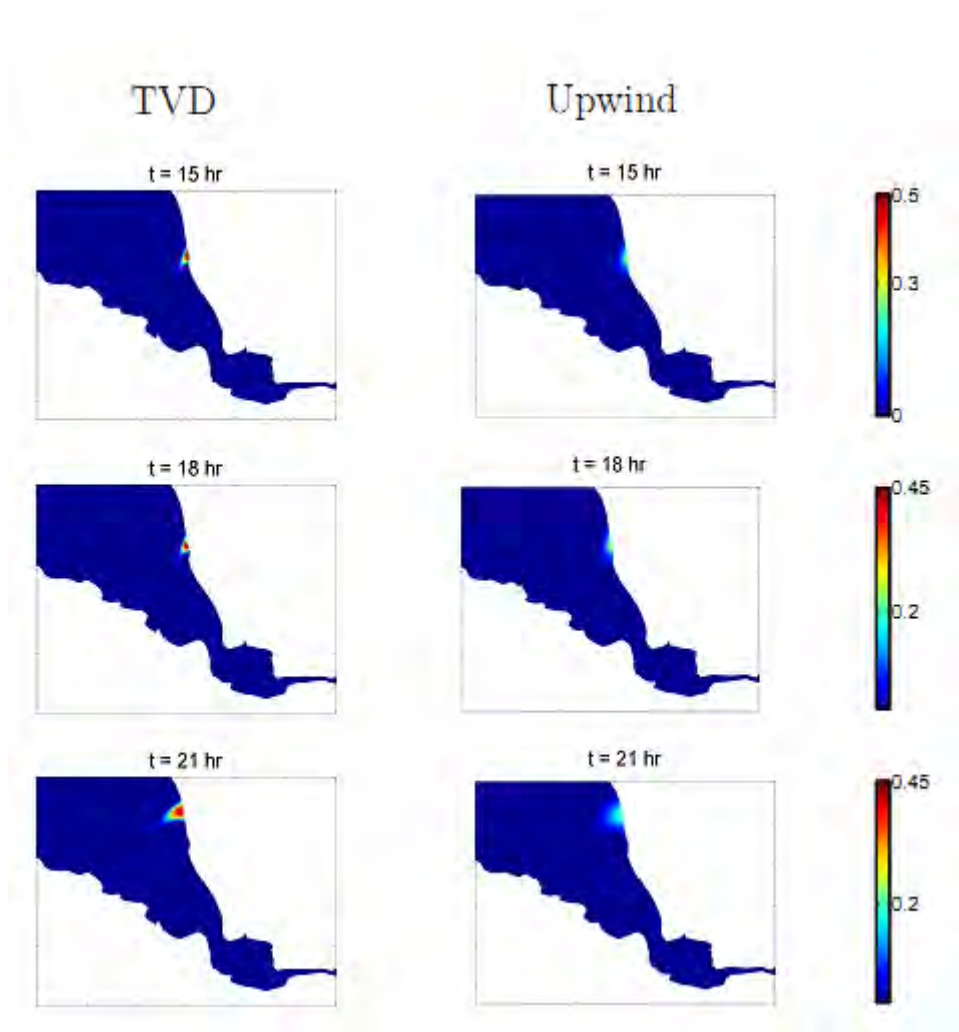




*Figure 3: Evolution of passive tracer field at Carquinez Strait from 15 to 21 hour in 3 hour intervals. Left column is the TVD scheme and right column is first-order upwind. Note that the color axes change with time.*

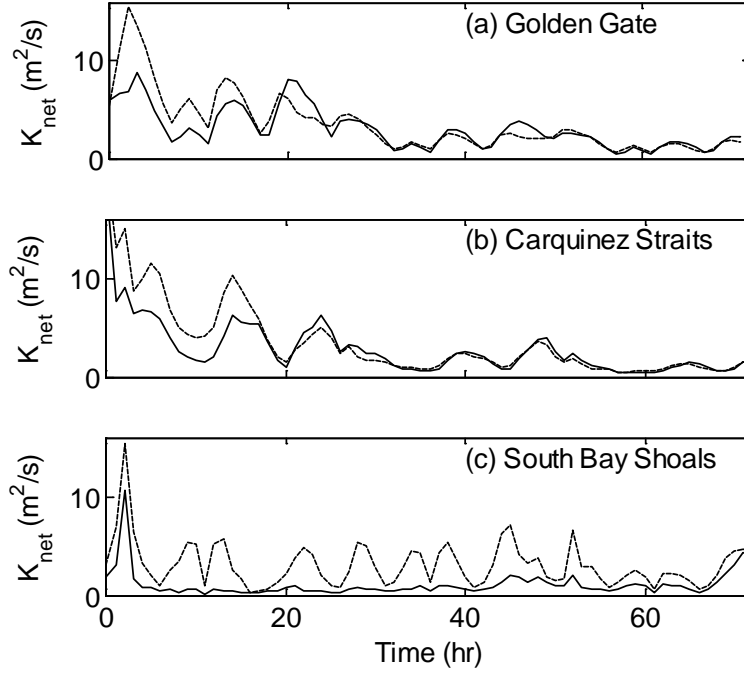


**Figure 4: Evolution of passive tracer field in South Bay from 0 to 12 hour in 3 hour intervals. Left column is the TVD scheme and right column is first-order upwind. Note that the color axes change with time.**

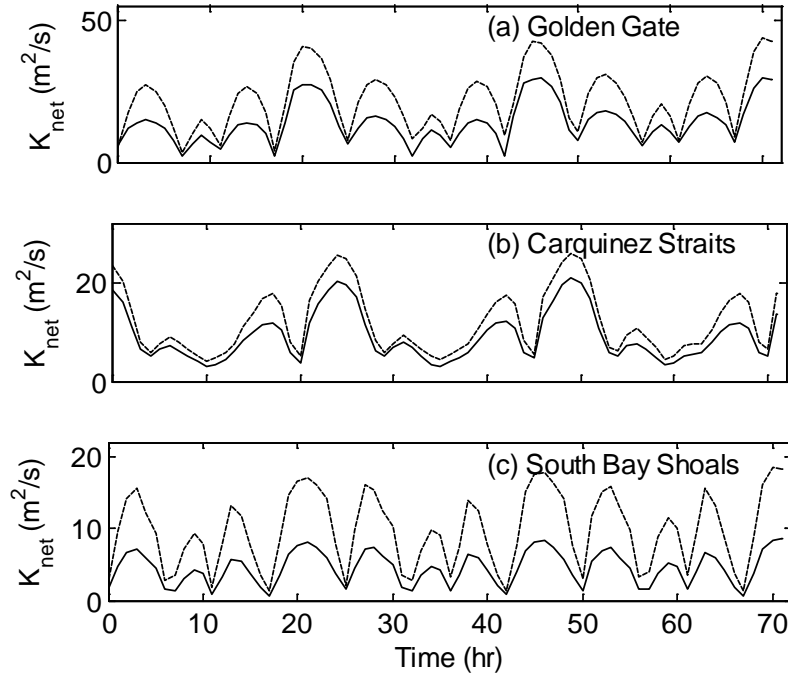


*Figure 5: Evolution of passive tracer field in South Bay from 15 to 21 hour in 3 hour intervals. Left column is the TVD scheme and right column is first-order upwind. Note that the color axes change with time.*





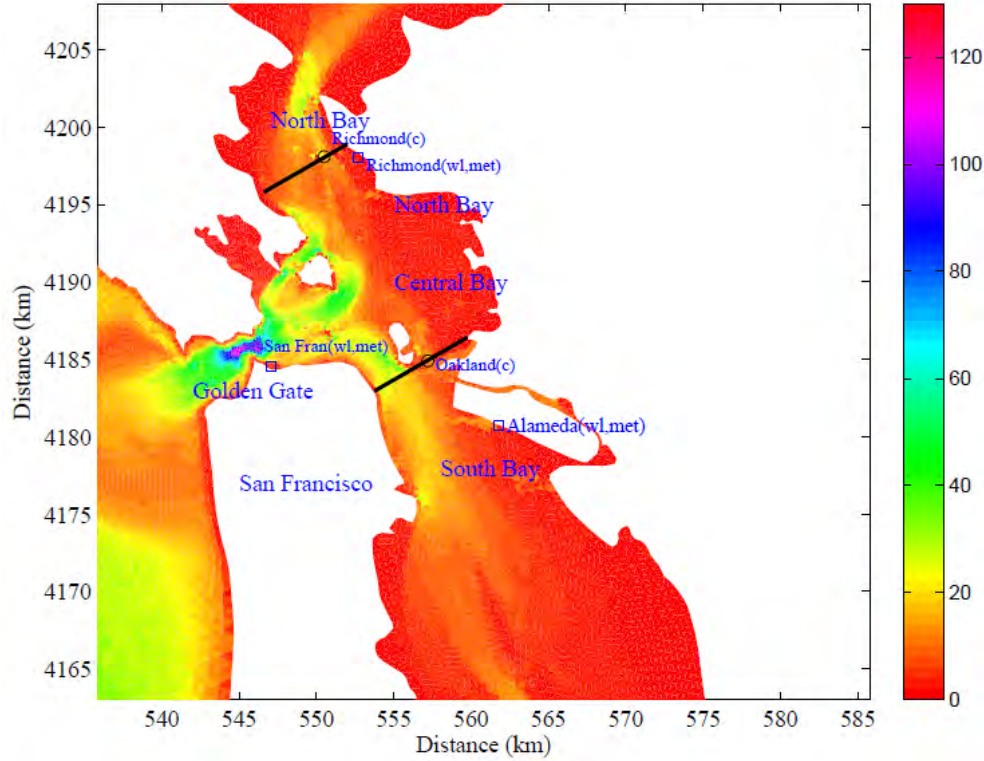
**Figure 6:** Time series of the numerical diffusion coefficient computed at three locations in San Francisco Bay using equation (1). Dashed line is the TVD scheme and the solid line is first-order upwind.



**Figure 7:** Time series of the numerical diffusion coefficient computed at three locations in San Francisco Bay using equation (1), but with the tracer field reinitialized every hour. Dashed line is the TVD scheme and the solid line is first-order upwind.

### *Low-frequency variability in San Francisco Bay*

To understand the behavior of low-frequency currents in San Francisco Bay, we use the San Francisco Bay SUNTANS model (*Chua and Fringer, 2011*) in its 2D (depth-averaged) mode and with a coarser grid. Figure 1 shows a detail of the study area along with the bathymetry with typical depths ranging from 10 to 35 m in narrow channels and broad shoals with depths less than 10 m. The average depth of the Bay is 6 m at Mean Low Low Water (MLLW) and the deepest section of the main channel is at the Golden Gate, where the depth is 110 m. The prevailing winds in San Francisco Bay area are from west and north-west.



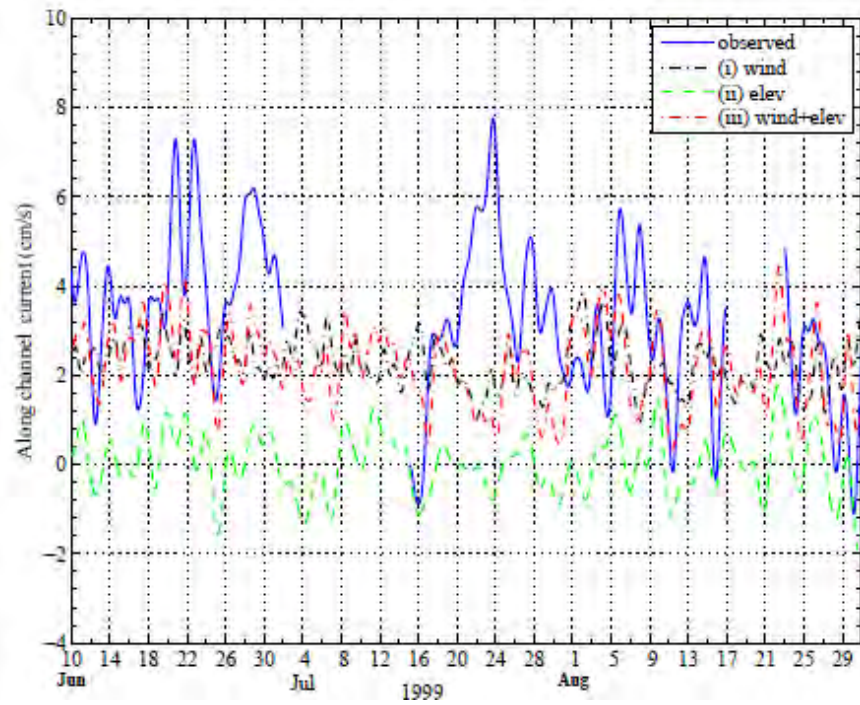
**Figure 8: San Francisco Bay study area and station locations overlaid over the bathymetry (in m below MSL). Legend : wl: water level, c: ADCP, met: meteorological station.**

The model grid consists of 28539 prismatic cells and extends 40 km west from the Golden Gate into the Pacific Ocean and to the western end of the Sacramento/San-Joaquin Delta. Simulations were run for a 120-day period (June-September 1999), using a time step of 10 seconds. A spin up time of 7 days was used to allow the model predictions to reach steady state. The bottom shear stresses are computed using the quadratic drag law, assuming a velocity profile that satisfies the log law with a  $Z_0$  value of 0.001. Hourly wind records obtained from a buoy near San Francisco are used as wind forcing which is assumed constant throughout the Bay. Surface wind stresses are estimated using a quadratic drag law, taking the surface drag coefficient to be 0.0015. Observed 40-hour low-passed water levels at Point Reyes are forced along the open boundaries to examine the effects of low-frequency coastal sea levels on the Bay. We ran three modeling scenarios to relate the forcing functions to the corresponding to observed low-frequency fluctuations in the Bay: (i) forced with winds, (ii) forced with low-frequency

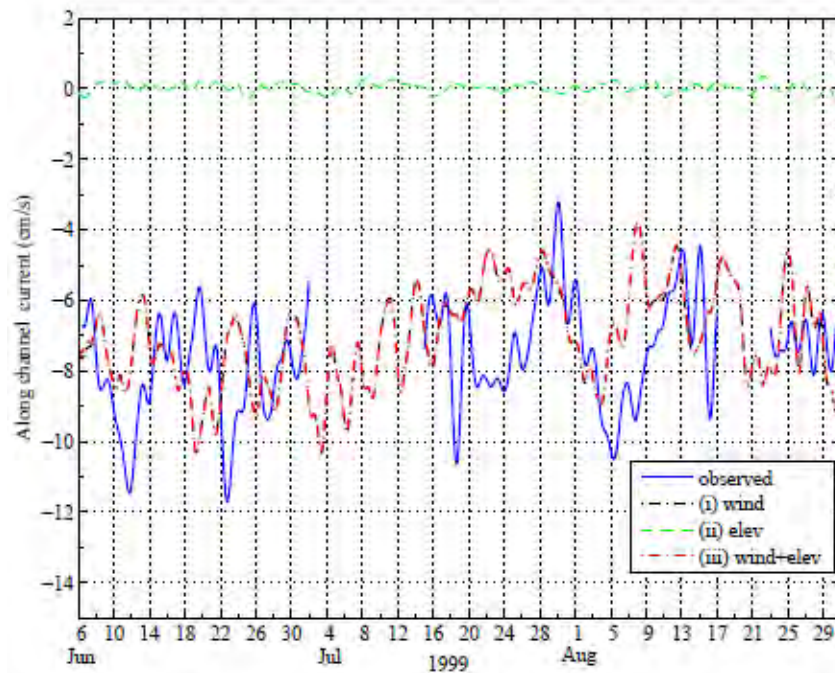
surface elevations, and (iii) forced with winds and low-frequency surface elevations at the Pacific Ocean boundary. No fresh water flows are imposed.

We compare the 40-hour low-passed observed currents due to the first principle component at the ADCP locations to the corresponding barotropic depth-averaged model-predicted currents obtained with the SUNTANS model. The model-predicted 40-hour low-passed depth-averaged currents at Richmond from the first scenario (forced with winds only) capture the mean upwind flow seen in the observation, as shown in Figure 9. However, the model-predicted low-frequency currents at Richmond do not capture the pulses of  $2\text{-}5\text{ cm s}^{-1}$  amplitude deviations from the mean that are seen in the observations. In the second scenario, we ran the model forced with observed low-frequency water levels at Point Reyes to examine the effects of low-frequency coastal sea levels on the currents in the Bay. Figure 9 shows that the model-predicted currents at Richmond due to coastal sea levels are less than  $1\text{ cm s}^{-1}$ . This implies that the influence of coastal sea-levels on the currents in San Francisco Bay is small relative to the effects of local winds. This is to be expected since the coastal sea-levels propagate in phase throughout the Bay, leading to weak or negligible pressure gradients. In the third scenario, we ran the model forced with both observed low-frequency water levels and winds. Figure 9(a) shows that model-predicted low-frequency currents at Richmond due to the combined effects of winds and low-frequency water levels are nearly the same as those due to winds alone. Figure 9(b) shows that the model-predicted 40-hour low-passed depth-averaged along channel currents at Oakland forced with observed winds from the Buoy at San Francisco compare well with depth-averaged observed ADCP currents due to the first PC. Like the results at Richmond, the model-predicted currents at Oakland due to the 40-hour low-passed observed low-frequency sea level forced along the open boundaries are negligible.

These results show that a large fraction of the low-frequency signal in the Bay arises from local wind forcing and that only a small fraction of the dynamics are due to offshore forcing. This has important ramifications for coupled ocean-estuary modeling because it implies that model error in predicting the wind-forced circulation must be small enough so as not to overwhelm the offshore wind-forcing effect. Additionally, the results show that the model predictions are not improved with the addition of forcing with offshore sea-level heights. This implies that the low-frequency offshore signal may be transmitted into the bay by some mechanism other than via barotropic low-frequency waves or that a constant offshore sea-level height is insufficient to transmit the full offshore signal into the Bay.



(a) *Oakland*



(b) *Richmond*

**Figure 9: Comparison of observed and model-predicted low-frequency currents at (a) Richmond and (b) Oakland, during the 1999 upwelling season for three different scenarios: (i) wind only (ii) elevations only and (iii) wind+elevations.**

## **IMPACT/APPLICATIONS**

The coupled simulation tool that is being developed for this project has the potential to form the basis for a wide range of modeling studies of other important coupled ocean-estuary systems.

## **RELATED PROJECTS**

The California Coastal Conservancy is funding the development of an open-source hydrodynamics and sediment transport model using SUNTANS to assess the impacts of marsh restoration projects on salt and sediment dynamics in San Francisco Bay. Fringer is involved in this project in collaboration with Profs. Mark Stacey and Zack Powell at U. C. Berkeley and Profs. Jeffrey Koseff and Stephen Monismith at Stanford University.

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